

Fission as a Hydrodynamic Micro-Explosion: A Testable Framework for High-Burnup Fuel Anomalies

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Abstract

Conventional diffusion-based fuel performance models have shown limitations in accurately predicting several important phenomena observed in high-burnup spent nuclear fuel (SNF). These predictive limitations are manifested in three principal areas: (1) the formation of the High Burnup Structure (HBS)—a distinctive microstructure characterized by both low-angle and high-angle grain boundaries that existing polygonization and recrystallization models insufficiently explain; (2) the occurrence of non-thermo-elastic "pulverization" within HBS regions during accident transients, which represents a mechanical degradation process distinct from conventional macro-cracking; and (3) the emergence of non-equilibrium chemical species, including volatile elemental iodine (I_2) and noble metal High-Entropy Alloys (HEAs). Collectively, these anomalies suggest a fundamental discontinuity in the standard thermodynamic framework governing fission energy partitioning. To address this gap, the present work introduces the Micro-Explosion (ME) Hypothesis. It is proposed that the mass defect arising from post-fission nucleon rearrangement is released as a physically liberated mass (m_{lib}), which subsequently undergoes an explosive transformation into a picosecond-scale shockwave. This shockwave is posited to constitute the primary mechanism governing local energy transfer and partitioning within the fuel matrix. The ME Hypothesis provides a unified mechanistic reinterpretation of several unresolved observations: HBS formation as shock-induced dynamic recrystallization, pulverization as shock-driven brittle decohesion, and HEA formation as non-equilibrium shock synthesis. This integrated framework establishes a coherent and experimentally testable foundation for advancing the understanding of fission energy dynamics and nuclear fuel behavior under extreme conditions.

Keywords: Nuclear Fission, Micro-Explosion Hypothesis, High Burnup Structure, Spent Nuclear Fuel, Shockwave, Mass Defect

1. Introduction: The Conventional Framework and Its Limits

The foundational framework for Uranium-235 fission describes the conversion of a mass defect (Δm) into approximately 200 MeV of released energy. Within this standard model, the partitioning of this energy is well-established [1]. The vast majority, approximately 168 MeV, is imparted as kinetic energy to the two primary fission fragments. This kinetic energy is conventionally attributed to the powerful Coulomb repulsion between these newly formed, highly positive daughter nuclei [1]. The remaining energy is partitioned into the internal excitation of these fragments, which subsequently de-excite via prompt neutron and gamma ray emission. The kinetic energy of all resulting particles is then rapidly dissipated as heat (phonons) within the UO_2 lattice [1, 2]. This model—predicated on energy transfer via Coulomb repulsion and subsequent thermal excitation—constitutes the thermal-diffusive framework that forms the conceptual basis for nuclear fuel behavior.

This foundational physical premise is not merely academic; it is the engineering basis codified into the entire suite of fuel performance codes (FPCs) governing reactor operation and safety licensing, including FRAPCON, BISON, and TRANSURANUS [3]. Because the primary energy transfer mechanism

is assumed to be thermal, these codes are by definition constructed upon coupled thermal-diffusive and thermo-mechanical principles. Fission gas release (FGR), for instance, is modeled exclusively as a thermally activated process, governed by the diffusion of single atoms through the UO_2 lattice [4]. Similarly, mechanical behavior is treated as a thermo-elastic response to temperature-induced stresses, while swelling is modeled as a predictable, semi-empirical function of burnup and temperature [3, 4]. These codes, and the conventional framework they represent, are demonstrably robust and well-validated—but only within their original operational envelope of low-to-moderate fuel burnup.

This framework, however, systematically fails when extrapolated into the "anomalous regime" of high burnup (e.g., > 60 GWd/MTU) and extended long-term storage [5]. When the empirical, thermal-diffusive models are pressed into these extreme conditions, they become fundamentally non-predictive [5]. A clear demonstration of this failure is the prediction of pellet-cladding mechanical interaction (PCMI) during power ramps. While FPCs accurately—or even slightly overpredict—cladding strain at low-to-moderate burnups, they systematically underpredict the measured strain at high burnups [6]. This divergence is not random error but a systemic failure, signaling that an unmodeled physical mechanism has become dominant.

The root of this failure is clear: current FPCs lack the explicit, physics-based models required to describe the novel microstructures and material properties that emerge in the high-burnup regime [5, 6]. This PCMI discrepancy is merely one symptom of a broad class of "unexplained" phenomena that now define the limits of the conventional model. These critical, unresolved anomalies include:

- **Anomalous Microstructural Reorganization:** The formation of the High Burnup Structure (HBS), a transformation in which the original $10\ \mu m\ UO_2$ grains are subdivided into a nanograin structure of 100–300 nm particles [7]. The fundamental mechanism for this reorganization has been "debated for decades" [8], as experimental evidence reveals contradictory signatures of both classical polygonization (low-angle grain boundaries) and recrystallization (high-angle grain boundaries), rendering both thermal models insufficient [8].
- **Non-Thermo-Elastic Mechanical Failure:** The fine fragmentation, or "pulverization," of HBS regions during accident transients [9]. This phenomenon is a non-thermo-elastic disintegration driven by the overpressure of large, micron-sized gas bubbles [10]. It was previously a "dropped" safety issue precisely because it is absent in low-burnup fuel, and conventional thermo-elastic fracture models cannot predict it [9, 10].
- **Non-Equilibrium Chemical States:** The failure of conventional thermodynamic equilibrium models. Such models predict the formation of stable, non-volatile Cesium Iodide (CsI). In high-burnup oxide fuel, however, a high oxygen potential "strips" the cesium, creating volatile, elemental iodine (I_2) [11]. Concurrently, noble metal precipitates (Mo-Ru-Pd-Tc-Rh) have been identified not as simple alloys, but as High-Entropy Alloys (HEAs)—a novel finding [12]. The formation of these HEAs is stabilized by configurational entropy, a non-equilibrium mechanism absent from standard thermodynamic databases [13].
- **Anomalous Fission Gas "Burst" Release:** The complete failure of diffusion-based FGR models to account for the "unexpected" enhanced gas release observed at high burnup (which is not correlated with temperature) [14], or the rapid "burst" release during transients, which is known to be mechanical and explicitly non-diffusional [15].

We posit that these are not disparate, isolated materials-science puzzles. They are, in fact, coupled symptoms of a single, flawed premise in the foundational physics of fission energy transfer: the conventional Coulomb-dominant, thermal-diffusive model is insufficient to describe the extreme high-burnup regime. This paper introduces an alternative foundational premise: the "Micro-Explosion" (ME) Hypothesis. This hypothesis posits that the dominant energy transfer mechanism is not Coulombic repulsion, but a picosecond-scale mechanical shockwave originating from the explosive transformation of the mass defect itself. The aim of this article is to formally define this hypothesis and demonstrate its superior explanatory power, arguing that this single, shock-dominant, ballistic/advective framework provides a unified and physically grounded mechanism for the entire class of anomalies that conventional models cannot resolve.

2. The Micro-Explosion (ME) Hypothesis: A New Fission Framework

The connection between binding energy and mass defect is governed by two fundamental principles: breaking a bond requires energy input, whereas forming a bond releases energy. Bond formation is therefore the driver of energy release. When a thermal neutron is absorbed by the nearly spherical U-235 nucleus, the system becomes the excited, unstable U-236^{*}

.This excited state, lasting only femtoseconds ($\sim 10^{-15}$ s), promptly scissions—most often into non-spherical daughter nuclei, such as barium and krypton, while emitting several prompt neutrons [1].

This initiation step is destabilizing. The conventional framework treats the resulting mass defect (Δm) as an abstract quantity of "missing mass" equivalent to the released energy ($E = \Delta mc^2$), which is then partitioned. The ME Hypothesis challenges this interpretation, not by refuting the equivalence, but by proposing a *physical mechanism* for the transformation.

At the instant of fission, the nucleons in the nascent daughter nuclei are captured in unstable, high-energy arrangements. To achieve stability, they must rapidly reorganize into new, more tightly bound configurations. We propose that this process, which involves the overlap of nuclear volumes, liberates the overlapped portion of matter, possibly to conserve the density and volume of each nucleon. This liberated, nuclear-density matter is the observed mass defect in U-235 fission. It is not mass that has "vanished" and "become" energy; it is mass that has been *expelled* from the newly forming, more tightly bound systems. This principle applies to both fission and fusion. In fission, a significant portion of the released energy thus originates from these post-fission rearrangements.

The ME Hypothesis, therefore, re-identifies the mass defect (Δm) as a discrete, physical, and liberated mass (m_{lib}). We formally state the Micro-Explosion (ME) Hypothesis as follows:

The liberated mass (m_{lib}) is a physical substance of immense energy density, possessing a vast internal potential (U_{ME}). Once released from nucleon bonding, this matter undergoes an explosive volumetric expansion. This rapid, picosecond-scale transformation is the primary motive force of fission, propelling the daughter nuclei and prompt neutrons apart via a mechanical shockwave. This mechanism is distinct from, and additive to, the subsequent, slower-acting Coulomb repulsion between the fragments.

This hypothesis does not challenge the mass–energy equivalence principle but rather its conventional interpretation as an abstract, passive conversion. Instead, the ME Hypothesis provides a physical pathway for that transformation, positing that the energy arises from the explosive transformation of

this liberated mass. This conceptual model can be formalized into a new framework for energy partitioning.

2.1. Total Energy (Q)

The total energy released, Q_{total} , is the sum of the explosive potential energy stored in the liberated mass, U_{ME} , and the residual excitation energy, E_{Frag}^* , left in the daughter nuclei after the ME event (which accounts for shape de-excitation, residual vibrations, etc.).

$$Q_{total} = U_{ME} + E_{Frag}^*$$

This Q_{total} is equivalent to the total mass defect as calculated conventionally. The potential U_{ME} is the energy equivalent of the liberated mass:

$$U_{ME} = m_{lib} \cdot c^2$$

2.2. Partitioning of the Explosive Potential

The explosive transformation converts U_{ME} into kinetic work, W_{ME} . This work is partitioned between the main fission fragments (Frag) and the prompt neutrons (ν).

$$U_{ME} \rightarrow W_{ME}$$

$$W_{ME} = W_{ME,Frag} + W_{ME,Neutrons}$$

Where $W_{ME,Neutrons} = E_{K,Neutrons}$ (~ 5 MeV), the observed kinetic energy of prompt neutrons [1].

2.3. Partitioning of Excitation Energy

The residual energy, E_{Frag}^* , is dissipated conventionally over a longer timescale (nanoseconds to years) via prompt and delayed gamma/beta decay.

$$E_{Frag}^* = E_{\gamma,prompt} + E_{\gamma,delayed} + E_{\beta} + \dots$$

Where $E_{\gamma,prompt} \approx 7$ MeV [1].

2.4. Total Fragment Kinetic Energy

This formulation leads to the central tenet of the model. The total measured kinetic energy of the fission fragments ($E_{K,Frag} \approx 168$ MeV) [1] is not from a single source. It is the sum of the work done by the explosive shockwave ($W_{ME,Frag}$) and the subsequent work done by Coulomb repulsion ($W_{Coulomb}$) as the fragments fly apart.

$$E_{K,Frag} = W_{ME,Frag} + W_{Coulomb}$$

Where the Coulomb term is the standard potential:

$$W_{Coulomb} = U_C = \frac{1}{4\pi\epsilon_0} \cdot \frac{(Z_1e)(Z_2e)}{R_{scission}}$$

This framework re-casts the conventional model as a special case where the ME Hypothesis is false (i.e., $m_{lib} = 0$ and $W_{ME,Frag} = 0$), leaving $E_{K,Frag} = W_{Coulomb}$ alone. This conventional Coulomb-dominant, thermal-diffusive model has, as demonstrated, proven insufficient to explain the anomalies outlined in Section 1. The ME Hypothesis, in contrast, proposes a shock-dominant, ballistic/advective model. This shift is not a minor correction; it implies that the primary damage mechanism in nuclear fuel is not slow, thermal diffusion, but rapid, picosecond-scale mechanical shock and non-equilibrium shock chemistry. As we will demonstrate in the following section, this single physical shift provides a unified and mechanistic explanation for the entire class of unresolved phenomena in high-burnup fuel.

3. Explanatory Power: Reinterpreting SNF Anomalies via Shock-Mechanics

The explanatory power of the Micro-Explosion (ME) Hypothesis is best demonstrated by its ability to resolve the cluster of anomalies—detailed in Section 1—that have long resisted explanation within the conventional, thermal-diffusive framework. The standard model's failure is systemic: it fundamentally misapplies equilibrium, thermo-elastic principles to a material environment that, we propose, is dominated by non-equilibrium, shock-mechanical processes.

When these anomalies are re-examined through the lens of the ME Hypothesis, wherein every fission event delivers a picosecond-scale mechanical shockwave, they cease to be disparate, paradoxical observations. Instead, they emerge as the predictable and coupled consequences of a material subjected to continuous, *in-situ* mechanical processing and shock-synthesis on an atomic scale.

3.1. The HBS Formation Anomaly: Shock-Induced Dynamic Recrystallization

The formation of the High Burnup Structure (HBS) is arguably the most profound microstructural change in high-burnup fuel, yet its fundamental mechanism remains "contentious" and "debated for decades" [8]. The central paradox lies in the experimental evidence. Post-irradiation examination (PIE) consistently reveals the simultaneous coexistence of features that are contradictory under conventional thermal models: low-angle grain boundaries (dislocation cells), the signature of polygonization, are found alongside high-angle grain boundaries (new, defect-free grains), the signature of recrystallization [7, 8]. Conventional frameworks, which treat these as distinct, sequential thermal processes, cannot account for a single physical mechanism that *necessarily* and *simultaneously* produces both. While some have hypothesized that polygonization may act as a nucleation site for recrystallization [7], the conventional framework lacks this unified mechanism.

The ME Hypothesis resolves this contradiction by reframing the mechanism as a non-equilibrium mechanical process, not a gradual thermal one. The ME shockwave acts as a form of severe plastic deformation (SPD), delivering repeated, localized, high-strain-rate impacts to the UO_2 lattice—a process analogous to high-energy ball milling [16]. In materials science, it is well-established that this exact mechanism, dynamic deformation and recrystallization, produces the "contradictory" microstructure observed in the HBS.

This single process provides the intense, localized strain energy to drive both outcomes concurrently: (1) The accumulation of dislocations from shock-induced damage and their rearrangement into "walls" or "cells" is polygonization, creating the observed low-angle boundaries. (2) At points of sufficient

localized strain, this same mechanical event provides the driving force to nucleate entirely new, defect-free grains.

Therefore, polygonization and recrystallization are not competing theories; they are the coupled, simultaneous products of a single underlying physical process: shock-induced dynamic recrystallization. The HBS is not a thermally evolved structure but a mechanically processed nanoceramic, forged by billions of micro-explosions. This unified mechanism provides a coherent physical explanation for the entire, previously "contentious," range of microstructural evidence.

3.2. Fuel Pulverization: Shock-Driven Mechanical Decohesion

Conventional thermo-elastic fracture models, validated on low-burnup fuel, predict only large, radial macro-cracks [3]. These models fail completely when applied to high-burnup fuel, which under transient conditions (e.g., LOCA) undergoes fine fragmentation, or "pulverization," into micron-sized particles [9]. This phenomenon, previously a "dropped" safety issue, is a non-thermo-elastic failure [9, 10]. The current leading hypothesis attributes this failure to the rapid overpressurization of large, micron-sized intergranular gas bubbles—a hallmark of the HBS—which violently exceeds the intergranular strength of the fine-grained structure, causing brittle "decohesion" [10]. This explanation, however, is incomplete: the conventional framework lacks a physical model for both the *initial condition* (the brittle, nanograined, porous HBS) and the *failure mechanism* (a trigger for mechanical decohesion) [9].

The ME Hypothesis provides the missing physics for both.

- **The Initial Condition:** As established in 3.1, the ME mechanism explains the creation of the HBS as a mechanically processed, nanograined material, which is known to be inherently brittle. Furthermore, it provides a non-diffusive mechanism for creating the large pores: the shockwave's "punching effect" would ballistically sweep and agglomerate insoluble fission gas atoms and nano-bubbles into the newly formed grain boundaries.
- **The Failure Mechanism:** The ME Hypothesis is the failure trigger. Pulverization is not a thermal shock event; it is a *mechanical* shock event. During a transient, the increased fission rate produces more frequent and energetic ME shockwaves. These impulses propagate through the pre-brittled, porous HBS, providing the picosecond, non-thermo-elastic force that, when coupled with the high internal bubble pressure [10], causes catastrophic, brittle decohesion and shatters the fuel.

Pulverization is the direct, mechanical failure of a shock-processed material—a mechanism entirely absent from conventional thermal models.

3.3. Non-Equilibrium Phase Synthesis: Noble Metal High-Entropy Alloys (HEAs)

A recent, novel discovery in SNF is that the 5-component noble metal precipitates (Mo-Pd-Rh-Ru-Tc), long known as the "epsilon-phase," are in fact High-Entropy Alloys (HEAs) [12]. This finding is profound: this phase is the only hexagonally-close-packed (HCP) HEA currently described in materials science [12]. Their formation is inexplicable by conventional, equilibrium thermodynamics; their stability is derived not from enthalpy of formation but from high configurational entropy [13]. Standard thermodynamic databases and codes, built on equilibrium principles, do not include this mechanism and thus cannot account for the formation or unique properties of these phases [12, 13]. How these exotic, non-equilibrium alloys are synthesized *in-situ* within a solid-state matrix represents a fundamental anomaly.

The ME Hypothesis offers a direct and elegant solution. The synthesis of HEAs requires *precisely* the conditions the ME provides. Cutting-edge materials synthesis techniques used to create HEAs—such as "flash thermal shocks" [17], "high-temperature liquid shock", and "shock synthesis"—function by mixing multiple elements and "freezing" them in a metastable, high-entropy state. This is achieved via ultrafast heating and cooling ramps ($> 10^4$ K/s) and a high-entropy environment that "rule out the possibility of phase separation" [17].

The Micro-Explosion is this process at the nanoscale. The fission event is a picosecond, high-temperature, high-pressure shock originating in a "soup" of the five HEA-forming elements (Mo, Pd, Rh, Ru, Tc). This event provides the non-equilibrium shock synthesis necessary to force these elements into a single, high-entropy phase. The conventional equilibrium model fails because the material is never in equilibrium. The fuel rod is acting as a nanoscale HEA shock-synthesis chamber, and the ME is the manufacturing process.

3.4. Atypical Chemistry and Transport: Iodine (I_2) and Fission Gas Release (FGR)

The conventional framework's reliance on equilibrium and diffusion fails in explaining both chemical speciation and fission gas transport.

- **Non-Equilibrium Chemistry:** Conventional thermodynamic models, which assume chemical equilibrium, predict that the volatile fission products Cesium (Cs) and Iodine (I) will readily combine to form the stable, low-volatility salt, CsI [18]. This is a foundational assumption for safety analysis. This assumption fails in high-burnup oxide fuel, where the high oxygen potential of the fuel "pulls cesium away from iodine" to form cesium uranates (e.g., Cs_2UO_4) and cesium molybdate (Cs_2MoO_4) [11]. This strips the Cs from CsI , leaving iodine to exist as highly volatile and radiologically significant elemental iodine (I_2) [11].

The ME Hypothesis replaces this failed equilibrium model with non-equilibrium shock chemistry. Fission products are not formed at low energy and allowed to slowly react; they are born from the explosive plasma of the ME. The chemical bonds that form are not the most thermodynamically stable, but the most kinetically-favored products "quenched" from this high-pressure, high-temperature, non-equilibrium state. From this perspective, it is plausible that stable CsI never forms in the first place, or is instantly dissociated. The observed elemental I_2 and cesium uranates are the direct, quenched-in end products of the ME's shock chemistry.

- **Anomalous Transport (FGR):** Conventional FGR models are entirely diffusion-based [3, 4]. These models completely fail to predict two key phenomena: (1) the "unexpected" and enhanced FGR at high burnup that is not correlated with fuel temperature [14], and (2) the rapid "burst" FGR during fast transients [15]. This burst release is explicitly "not well captured by fuel performance codes" and is known to be a mechanical process linked to micro-cracking and planar separation along grain boundaries [15].

The ME Hypothesis provides the missing physical mechanism for both, replacing thermal diffusion with ballistic/advective transport.

- **Athermal Release:** The ME shockwave provides a ballistic ejection mechanism. If a fission event occurs near a free surface (a grain boundary or crack), fission gases (Xe, Kr) are mechanically propelled or "punched" into the free volume by the shock's force. This provides a direct, athermal, ballistic process, explaining the gas release that is not correlated with temperature [14].

- **Burst Release:** The ME shockwave is the mechanical failure mechanism. During a fast power transient, the rapid succession of shocks acts as a hammer, propagating micro-cracks along the pre-brittled grain boundaries of the HBS [15]. These cracks "open the grain boundary" and provide a short-circuit, advective pathway for all the gas trapped in the HBS pore network to be released in a "burst" [15].

In every case, the ME Hypothesis provides a single, consistent, shock-mechanical framework that coherently explains the cluster of anomalies that the conventional, thermal-diffusive model cannot.

4. Proposed Falsifiable Tests

A physical hypothesis, however compelling its explanatory power, must be grounded in empiricism and offer predictions that are subject to experimental falsification. The Micro-Explosion Hypothesis makes concrete physical claims that differ from the conventional framework, leading to distinct, measurable signatures. This section proposes three experiments designed to probe these signatures. Each experiment targets a different physical consequence of a hydrodynamic fission event—acoustic, structural, and kinematic—and is designed to provide a clear verdict on the validity of the hypothesis.

4.1. Experiment 1: Acoustic Signature Detection

4.1.1. Principle

An explosion is fundamentally a mechanical event that generates a pressure wave. If each fission is a micro-explosion, it must generate a high-frequency acoustic signature—a shockwave—that propagates through the solid medium. The detection of such an acoustic pulse, temporally correlated with a fission event, would provide direct evidence of a mechanical energy release mechanism. Acoustic Emission (AE) is an established technique for detecting transient elastic waves from localized stress-energy release (e.g., microfracture) and is ideal for this investigation [19].

4.1.2. Experimental Setup

A small, thin sample of fissile material (e.g., ^{235}U foil) would be placed in a controlled neutron flux. A high-frequency, radiation-hardened piezoelectric acoustic sensor would be directly coupled to the sample holder [20]. A separate detector array would monitor for coincident neutron and gamma emissions, which provide the precise timestamp for a fission event [19]. The experiment would then search for a temporal correlation between the fission trigger and a signal from the acoustic sensor [19].

4.1.3. Predicted Outcome and Falsification

The hypothesis would be validated by the detection of a sharp, broadband acoustic pulse that is precisely correlated with individual fission events [19]. The waveform should be characteristic of a shockwave, with a rapid rise time, distinguishing it from background thermal noise [19]. Conversely, the absence of any such fission-correlated acoustic signal, after accounting for signal attenuation and sensor sensitivity, would strongly falsify the hypothesis, indicating that the energy is released through non-mechanical channels as described in the standard model [19].

4.2. Experiment 2: Ultrafast Lattice Dynamics (XFEL)

4.2.1. Principle

The most direct test of the hypothesis is to observe the lattice response in real time [21]. A fission micro-explosion should generate a coherent, mechanical shockwave propagating through the crystal lattice on a picosecond timescale [22]. This phenomenon can be captured with modern pump-probe techniques using X-ray Free-Electron Lasers (XFELs) [21].

4.2.2. Experimental Setup

Using an XFEL, a thin fissile target (e.g.,

^{235}U) would be irradiated with a pulse to induce fission (the "pump," e.g., a neutron pulse or high-intensity laser pulse) to generate a diffraction pattern [21]. By varying Δt from femtoseconds to picoseconds, a "movie" of the lattice response can be constructed [21]. This technique has been successfully used to image transient strain and shock propagation in other materials [22].

4.2.3. Predicted Outcome and Falsification

The hypothesis predicts the observation of transient shifts or broadening in the diffraction peaks, consistent with a propagating compression wave originating from a point source [22]. This would provide strong evidence for a shockwave [22]. Falsification would occur if the diffraction patterns only show a gradual, isotropic increase in thermal vibrations (i.e., the Debye-Waller factor) without evidence of a coherent compression wave [21]. This latter result would support the conventional thermal spike model [2].

4.3. Experiment 3: Fragment Emission Collinearity

4.3.1. Principle

The conventional model assumes that the two primary fission fragments are accelerated by a two-body Coulomb repulsion, requiring them to be emitted collinearly (at 180 degrees to each other) in the center-of-mass frame [1]. The Micro-Explosion Hypothesis, however, posits that the fragments are propelled by the expansion of a third entity—the liberated mass defect. This explosive component could impart a transverse momentum, resulting in a non-collinear emission.

4.3.2. Experimental Setup

This test requires a high-precision spectrometer capable of measuring the precise energy and vector momentum of both fission fragments from a single event in coincidence [23]. Advanced spectrometers, such as those based on the 2E-2v (double-energy, double-velocity) method, can achieve this [23]. A thin fissile target (e.g., ^{252}Cf for spontaneous fission or ^{235}U in a thermal neutron beam) would be placed at the center of a vacuum chamber, surrounded by position-sensitive time-of-flight and energy detectors [1, 23]. These detectors would record the energies and trajectories of the two coincident fragments on an event-by-event basis [23].

4.3.3. Predicted Outcome and Falsification

The hypothesis would be supported if a statistically significant number of binary fission events show a non-collinear emission (a measurable deviation from a perfect 180-degree separation) in the center-of-mass frame. This would imply a third, explosive component contributing to the momentum balance. Conversely, if, to the highest achievable precision, all binary fission fragments are found to be emitted collinearly with kinetic energies perfectly explained by the Coulomb force, this would invalidate a key kinematic prediction of the Micro-Explosion model [1].

5. Discussion and Implications

The implications of this shock-dominant framework, if validated, extend from applied nuclear engineering to foundational physics.

In the applied domain, the hypothesis directly challenges the foundational premise of conventional fuel performance codes (FPCs) like BISON, FRAPCON, and TRANSURANUS [3]. These codes are constructed upon coupled thermo-mechanical equations, modeling transport phenomena such as fission gas release as thermally activated, diffusion-based processes. By positing that the primary damage, restructuring, and transport mechanism is, in fact, shock-mechanical, the ME Hypothesis provides a physical explanation for the well-documented, systemic failures of these codes when extrapolated to the high-burnup regime [5]. This perspective offers a mechanistic basis for why codes like FRAPCON systematically underpredict pellet-cladding mechanical interaction (PCMI) strain at high burnup [6] and illuminates their necessary reliance on empirical correlations, rather than predictive physics, for HBS formation and its consequences.

Beyond reactor operations, the ME Hypothesis provides a new paradigm for long-term storage and disposal. It reframes the High Burnup Structure (HBS) not as conventional crystalline UO_2 , but as a mechanically activated, nanograined ceramic. Materials in this state possess fundamentally different, and typically higher, surface reactivity. This perspective may resolve the flatly contradictory data in the literature regarding the role of moisture in low-temperature fuel oxidation [24], where some studies report no effect and others report a large increase [24]. It also offers a coherent explanation for the "lack of consistency in the literature data" surrounding synergistic repository effects, where the dissolution rate is governed by an unquantified competition between radiolytic oxidants (e.g., H_2O_2) and corrosion-produced reductants (e.g., H_2) [24]. The ME Hypothesis suggests the reaction kinetics are dominated by the mechanical shock history of the fuel—a critical variable not accounted for in conventional thermodynamic or kinetic models.

Finally, at the level of foundational physics, the ME Hypothesis offers a tangible, mechanistic process for mass-energy conversion. It moves the discussion beyond an abstract equivalence principle by proposing a causal pathway: the formation of stronger nuclear bonds liberates a physical mass (m_{lib}), which subsequently undergoes an explosive volumetric transformation to perform kinetic work. This provides a physical, causal, and ultimately testable model for how the "missing mass" becomes the dominant kinetic energy that defines the fission process.

6. Conclusion

Conventional, thermal-diffusive models for nuclear fuel behavior have proven insufficient to explain a critical class of anomalies observed in high-burnup spent nuclear fuel (SNF). These systemic failures to predict phenomena ranging from microstructural reorganization to non-equilibrium chemistry and mechanical failure signal a fundamental gap in our foundational understanding of fission energy transfer.

This paper has introduced the Micro-Explosion (ME) Hypothesis as a single, unified, and physically grounded alternative. This framework posits that the mass defect, conceptualized as a liberated mass (m_{lib}), undergoes an explosive transformation that generates a picosecond-scale mechanical shockwave, supplementing the conventional Coulomb repulsion. We have demonstrated that this single, shock-dominant premise coherently re-frames the entire suite of unexplained anomalies, revealing them as coupled, mechanistic consequences of shock-physics.

Within this framework, the "contentious" formation of the High Burnup Structure (HBS) is reinterpreted as shock-induced dynamic recrystallization [7, 16]. Catastrophic fuel "pulverization" is recast as a predictable, shock-driven brittle decohesion rather than a purely thermo-elastic failure [9, 10]. Finally, the emergence of exotic phases, such as noble metal High-Entropy Alloys (HEAs) [12] and volatile elemental iodine (I_2) [11], is explained as a direct result of non-equilibrium shock synthesis and shock chemistry [13, 17].

The ME Hypothesis is not only empirically testable but also resolves these long-standing paradoxes. It thereby provides a more robust and physically sound foundation for the next generation of predictive modeling for nuclear materials.

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